SRF cavities for Z operation, 1 versus 2 cell

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Introduction

Highest beam current & lowest RF voltage for Z mode:
→ Base1-cell cavity design is straightforward and optimal choice

As 2-cell cavities are considered for W, H, and $t\bar{t}$ (+5-cell 800 MHz cavities), avoiding 1-cell design could:

RF-related accelerator parameters *(K. Oide, 29.05.2024)*

	Energy (GeV)	Current (mA)	RF voltage (GV)	Energy loss / turn (GeV)
Z	45.6	1283	0.079	0.039
W	80	135	1	0.369
H	120	26.7	2.08	1.86
$t\bar{t}$	182.5	5	11.67	9.94

- Rationalize RF resources during the development process (3 → 2 cavity types)
- Simplify the installation sequence (no cryo-module removal)
- Result in potential savings (cost, manpower, and time)

Outline

Baseline 1-cell design is compared with 2 alternative scenarios:

- 56 2-cell cavities per beam initially installed (76 added for W)
- 132 2-cell cavities remain for all modes

Aspects under consideration:

- Beam loading
  - Steady-state compensation
  - Instability due to fundamental mode
- Coupled-bunch instabilities due to higher-order modes (HOM)
  - Longitudinal and transverse
- Higher-order-mode power losses
- Availability challenges

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Steady-state beam loading

RF power for SRF cavities with circulators is minimized for optimal parameters:

Optimal detuning $\Delta\omega_{opt} = -\dfrac{\omega_{\mathrm{RF}}(R/Q)\ I_{b,DC}\sin\phi_s}{V_{\mathrm{cav}}}$

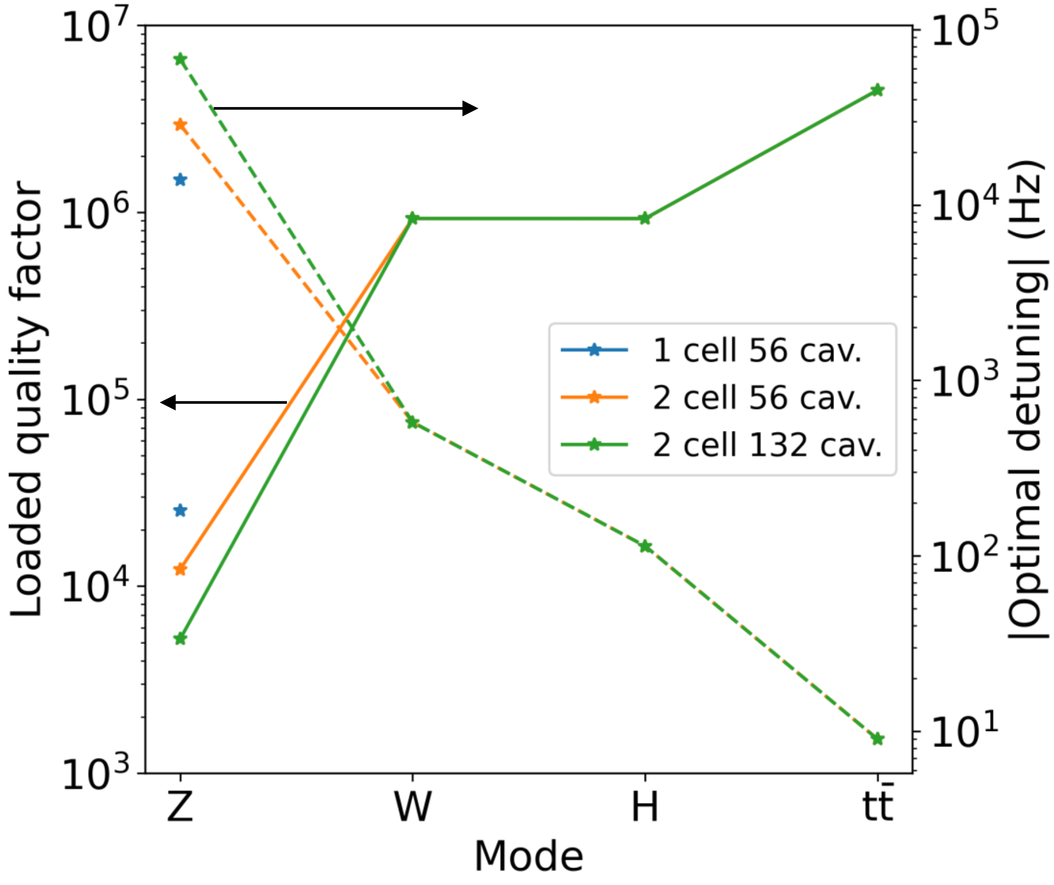
Optimal quality factor $Q_{L,opt} = \dfrac{V_{\mathrm{cav}}}{2(R/Q)I_{b,DC}\cos\phi_s}$

Increasing (R/Q) (43.8→90.6 Ohm) and reducing V_{cav}:

→ Large range for $Q_{L,opt}$ adjustment (a factor of ~75-600) starting from $\sim 5 \times 10^3$: possible FPC solutions under study *(S. Gorgi Zadeh and E. Montesinos, CERN SRF, 2024;*
see also slides of F. Gerigk)
→ Incresed detuning enhances instability due to fundamental mode

Can the total voltage be increased for Z mode?

Optimal parameters for different scenarios



Coupled–bunch instabilities due to fundamental mode

Standard analysis: compute growth rates and compare them with synchrotron radiation damping time

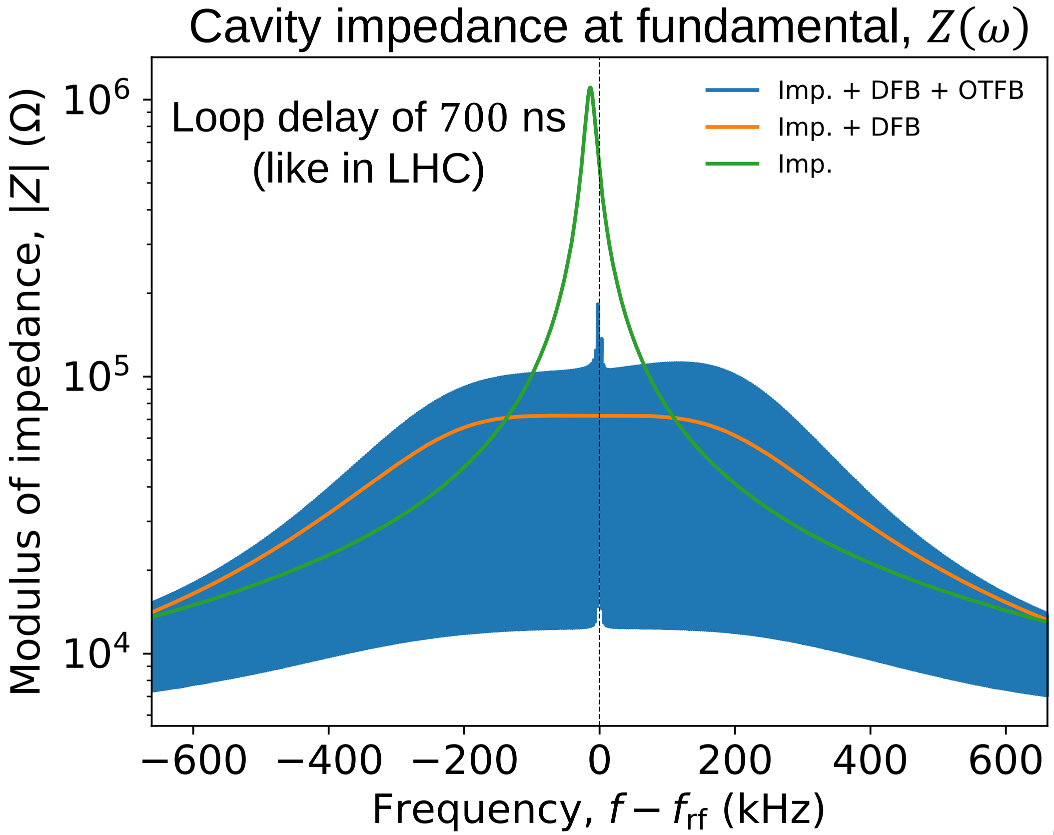
For short Gaussian bunches, the growth rate of the mode *m* is *(J. L. Laclare, 1985)*

$$\frac{1}{\tau_m} \approx \frac{e\eta I_{b,DC} V_{\text{tot}}}{4\pi E_b Q_s} \frac{\omega_{\text{RF}}}{V_{\text{cav}}} \{\text{Re}[Z_{\text{eff}}(\omega_+)] - \text{Re}[Z_{\text{eff}}(\omega_-)]\},$$

with $\omega_\pm = \omega_{\text{RF}} \pm (m + Q_s)\omega_{\text{rev}}$

Direct (DFB) and long-delay feedback (OTFB) systems can reduce impedance “seen” by the beam *(F. Pedersen, 1992)*

$$Z_{\text{eff}}(\omega) = \frac{Z(\omega)}{1 + \underset{\substack{\uparrow \\ \text{Feedback transfer function}}}{H_{FB}(\omega)} Z(\omega)}$$



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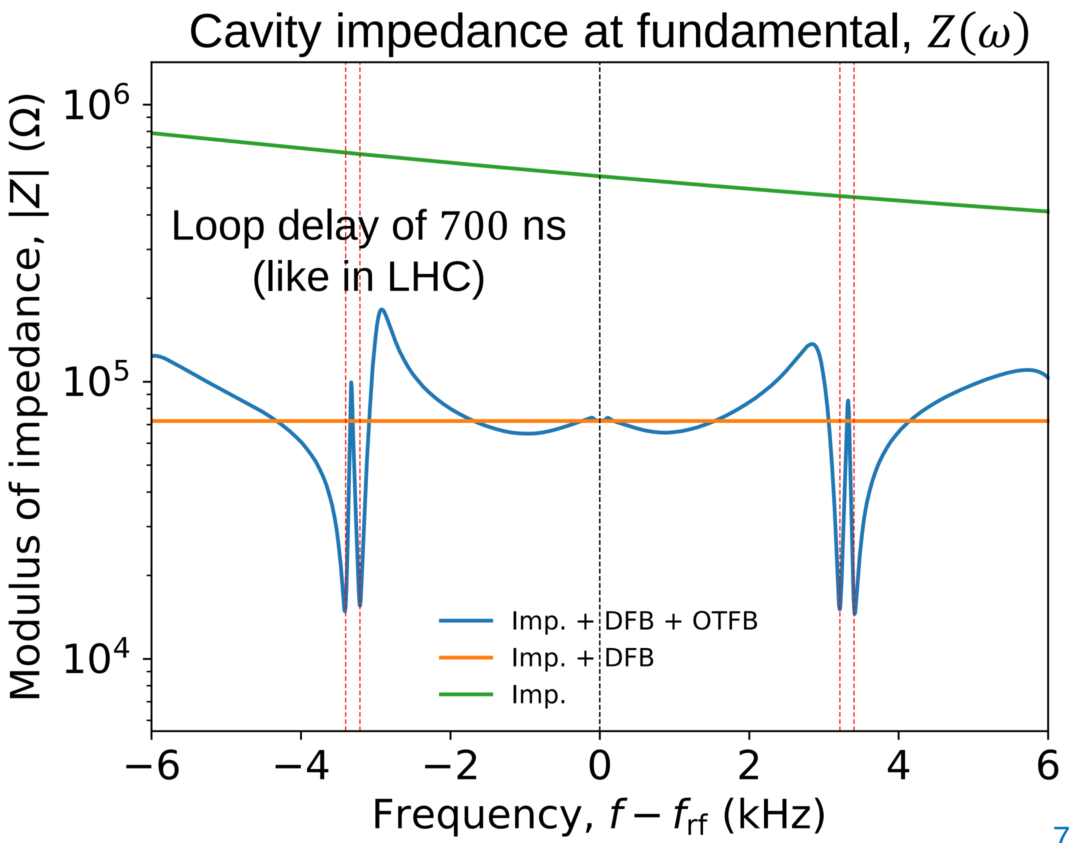
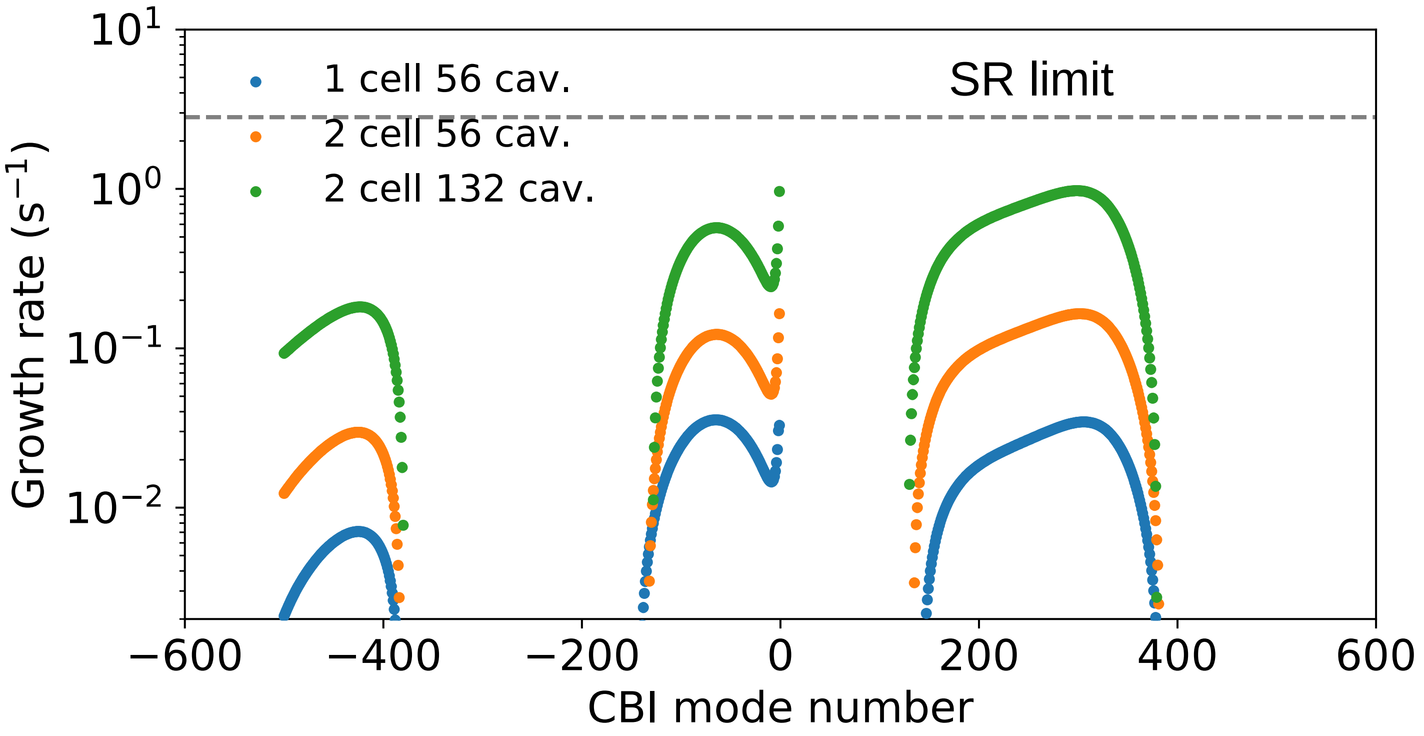


Instability growth rates

Calculations for loop delay of 700 ns, DFB gain 10, OTFB gain 20



Beam parameters according to *K. Oide, 29.05.2024*

Stability is significantly degraded for 2-cell scenarios (up to an order of magnitude), but feedback systems keep growth rates below the SR damping rate (a factor 4 margin for 132 2-cell cavities)

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  - Steady-state compensation
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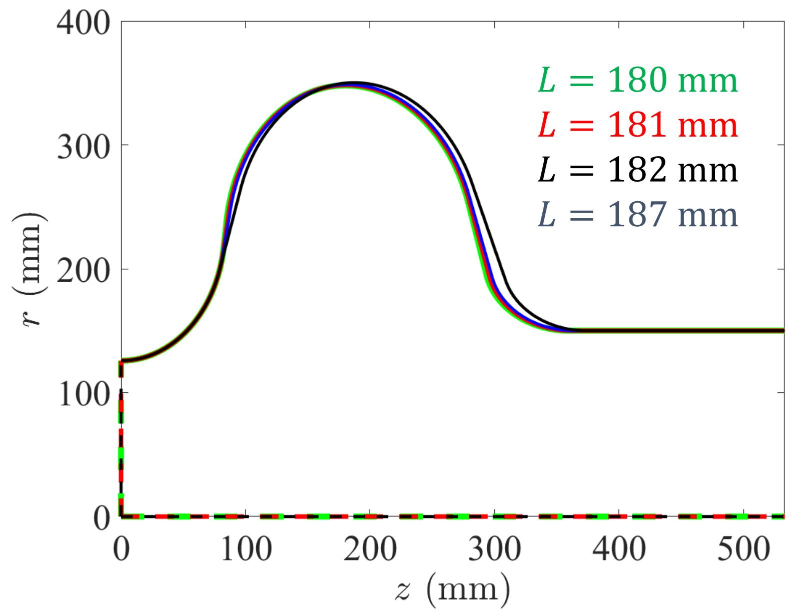
HOM-driven coupled-bunch instabilities

Longitudinal plane:

- No trapped HOMs → impedance at least a factor of 10 below the threshold even for 2-cell 132 cavities
- 2-cell cavities have 0-mode at 398.075 MHz with $(R/Q) = 0.3$ Ohm
  - Only twice below SR damping limit for $Q_L = Q_{L,opt}$ (might be larger due to limited bandwidth of circulator)
  - Possibility to reduce (R/Q) is under study to avoid need for additional longitudinal feedback system

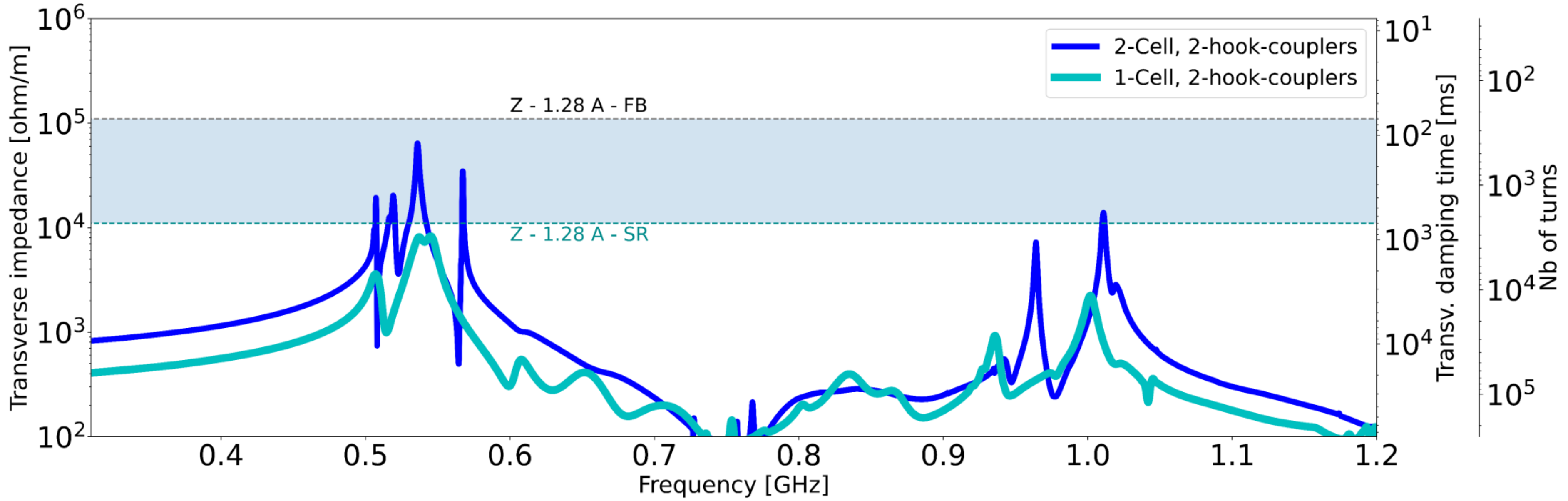
$L_i = L_e$ [mm]	R_{eq} [mm]	f [MHz]	R/Q_π [Ω]	R/Q_0 [Ω]	G [Ω]	E_{pk}/E_{acc} [-]	B_{pk}/E_{acc} [mT/MV/m]	α_i & α_e [degrees]
187	350.190	400.791	90.6	0.32	234.7	2.0	5.33	104.4 & 109.0
182	348.648	400.786	90.7	**0.037**	229.8	2.04	5.24	99.6 & 105.7
181	348.310	400.786	91.3	**0.014**	228.9	2.05	5.23	98.1 & 104.9
180	347.961	400.786	91.1	**0.002**	227.8	2.06	5.22	96.1 & 104.1

Courtesy of S. Gorgi Zadeh



HOM-driven coupled-bunch instabilities

Transverse plane:



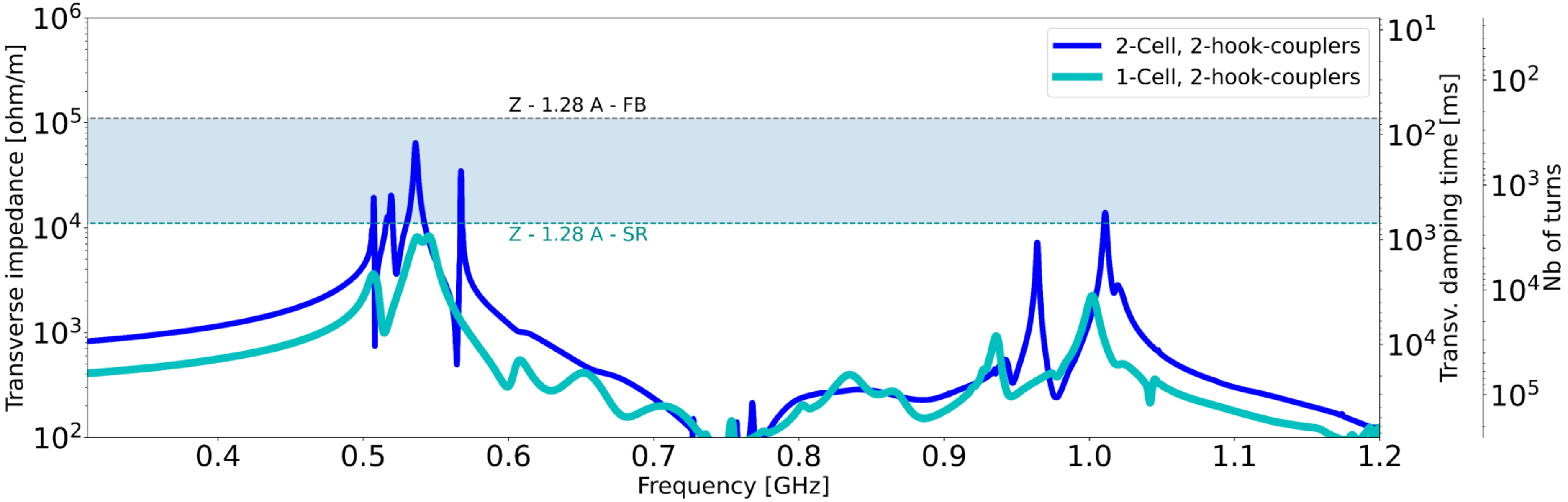
1-cell 56 cavities:

- Only 30% margin due to synchrotron radiation
- A very fast transverse feedback system (TFB) is needed for resistive-wall instability with ~3 turns growth time *(see slides of M. Migliorati)*

→ Adapting signal processing of TFB, ~200 turn damping time gives an order of magnitude margin also for HOM-driven instability

HOM-driven coupled-bunch instabilities

Transverse plane:



2-cell 56 (132) cavities:

- 165 (70) mA is required to have the same margin as the 1-cell design
- TFB is obligatory for stability, while the margin depends on damping speed;

~100(50)-turn damping time → a factor of 3.5

→ Performance and integration of TFB should be carefully studied

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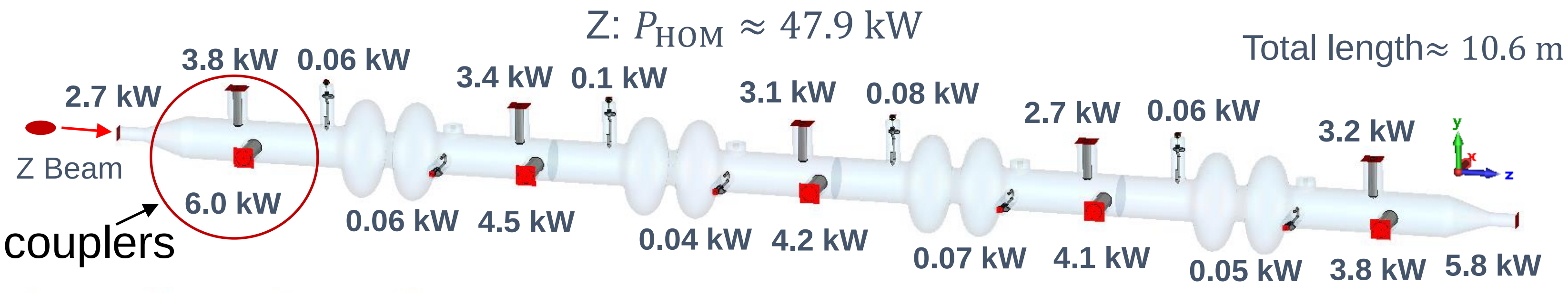
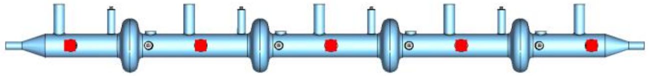
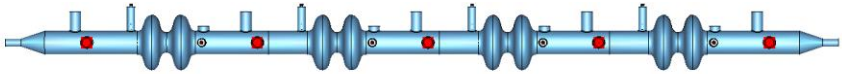
Higher-order mode power

$$P_{\mathrm{HOM}} = I_{b,\mathrm{DC}}^{2} \sum_{k=-\infty}^{\infty} \mathrm{Re}[Z(kf_{\mathrm{rev}})]|I_k|^2$$

In absence of resonant modes → $P_{\mathrm{HOM}} = k_{\parallel,\mathrm{HOM}} I_{b,\mathrm{DC}} Q_b$







HOM power for 1-cell 400 MHz module beamstrahlung bunch length:

P_{HOM} [kW] $\approx$ 8.9 + 5 × 1.5 +4 × 3.7 = 31.2

Tapers 2-coax couplers Cavities

HOM power for 2-cell 400 MHz module beamstrahlung bunch length:

P_{HOM} [kW] $\approx$ 8.9 + 5 × 1.5 +4 × 6.7 = 43.2

Courtesy of S. Gorgi Zadeh

Unavoidable 12 kW increase in HOM power due to double-cell design and potentially up to 10 kW deposited in resonance mode

→ "2-coax concept" must be experimentally demonstrated *(see slides of F. Peauger)*

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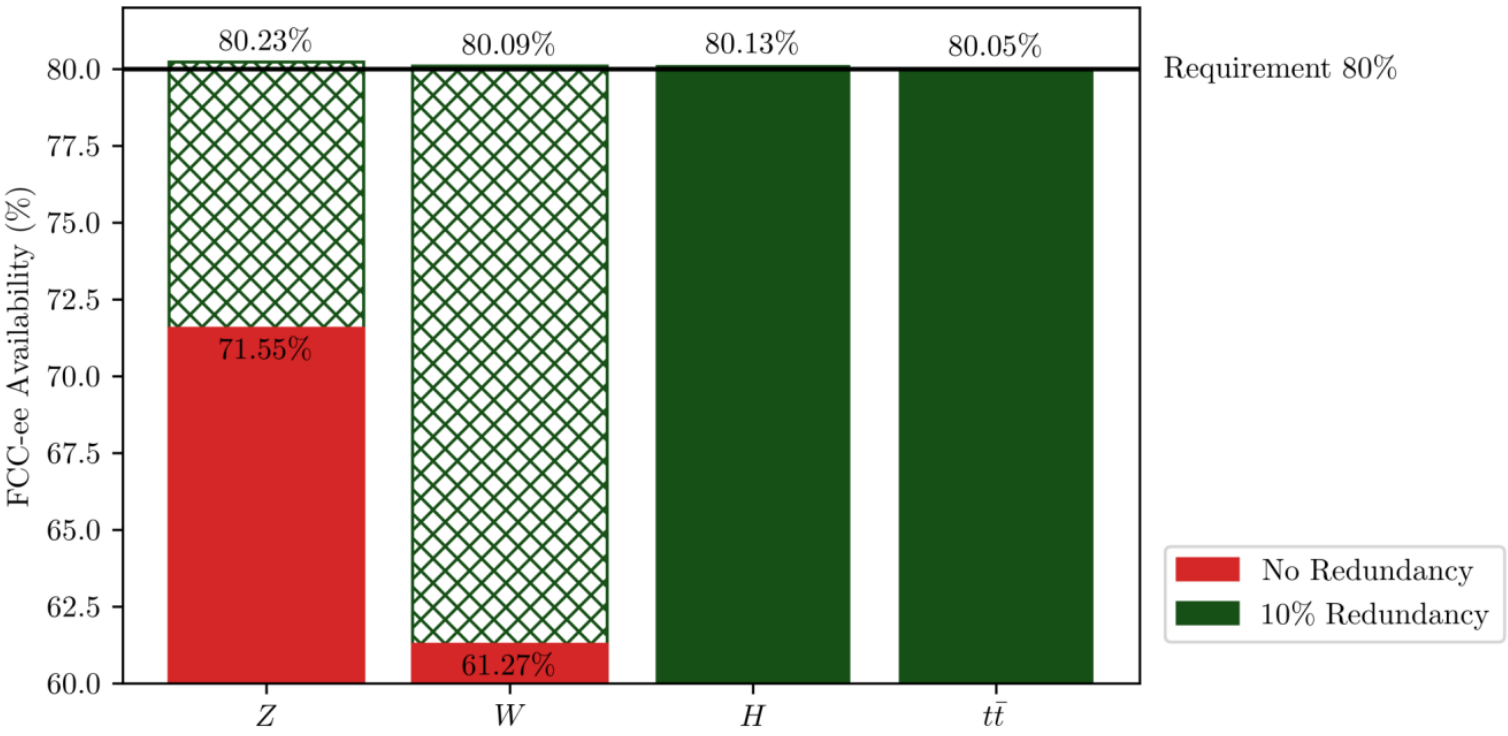
Availability challenges



Availability goals require 10% (minimum 4%) redundancy of the RF system *(see slides of J. Heron)*

Critical questions for Z mode:

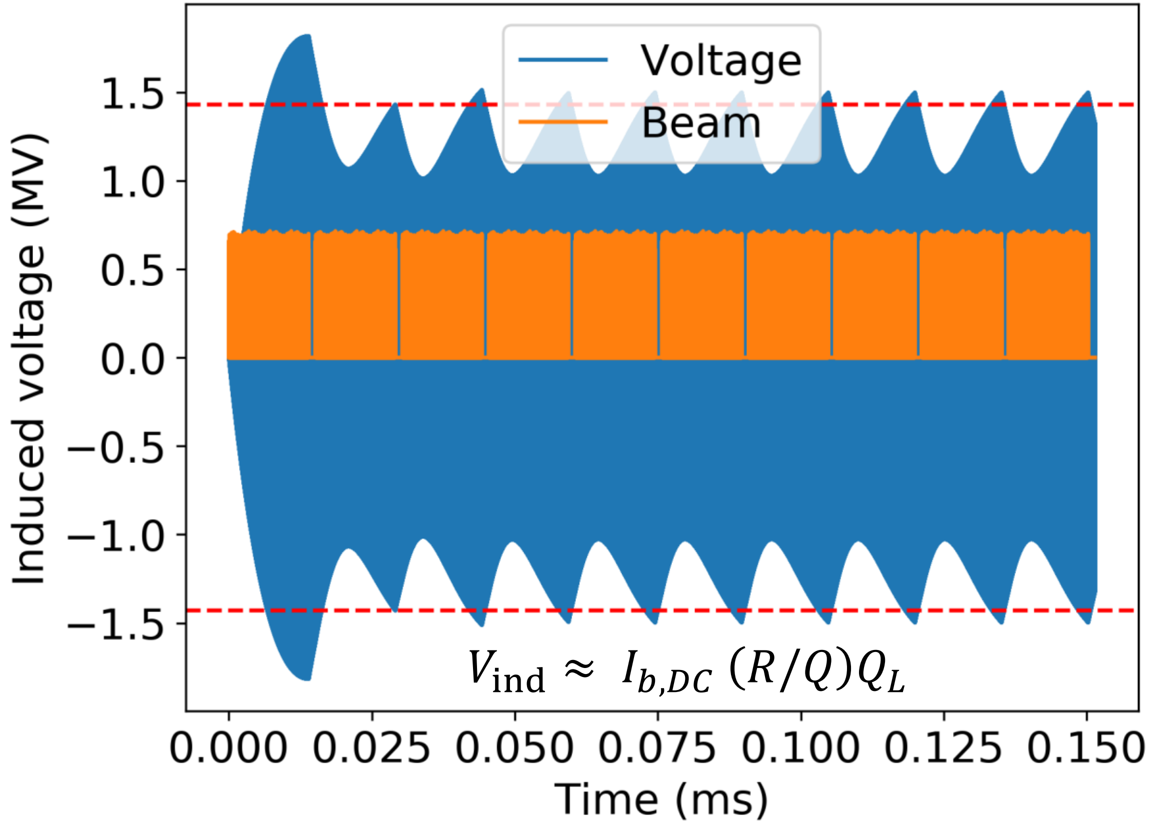
- Cavity damage due to strong beam-induced fields
- Coupled-bunch instability due to fundamental impedance
- Missing RF voltage

Beam-induced fields

For 1-cell and 2-cell designs, beam-induced voltage is comparable to the cavity voltage with RF ON since optimum parameters (detuning and Q_L) are used

→ No need for a fast-detuning system
→ Final assessment depends on transient analysis (ongoing)

Example of calculations with BLonD for 2-cell design

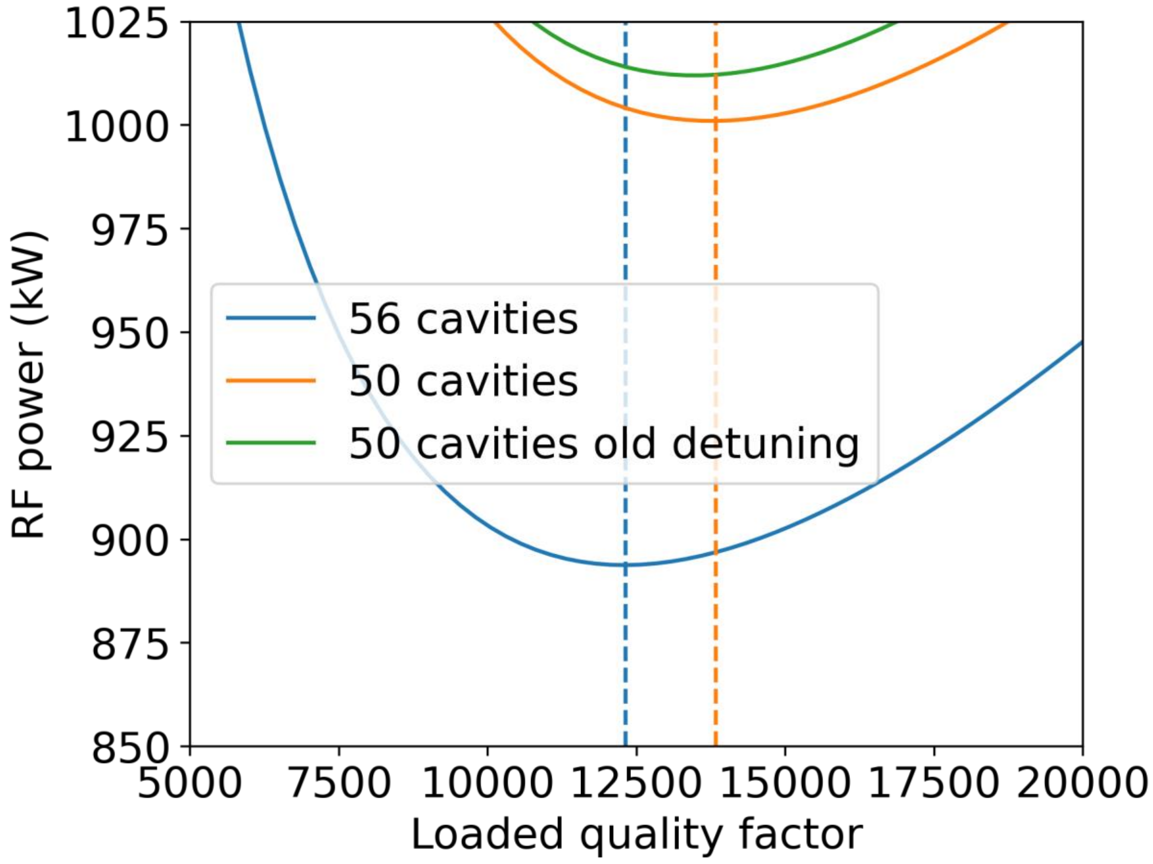


RF power overhead

To keep the same total voltage:
- RF voltage per cavity should be increased
- Detuning and Q_L can be kept constant (<10 kW of extra power)

RF power per cavity should be increased from 0.9 to 1 MW to compensate for 10% fewer cavities

Input RF power for optimum detuning for two scenarios (2-cell 56 cavities)



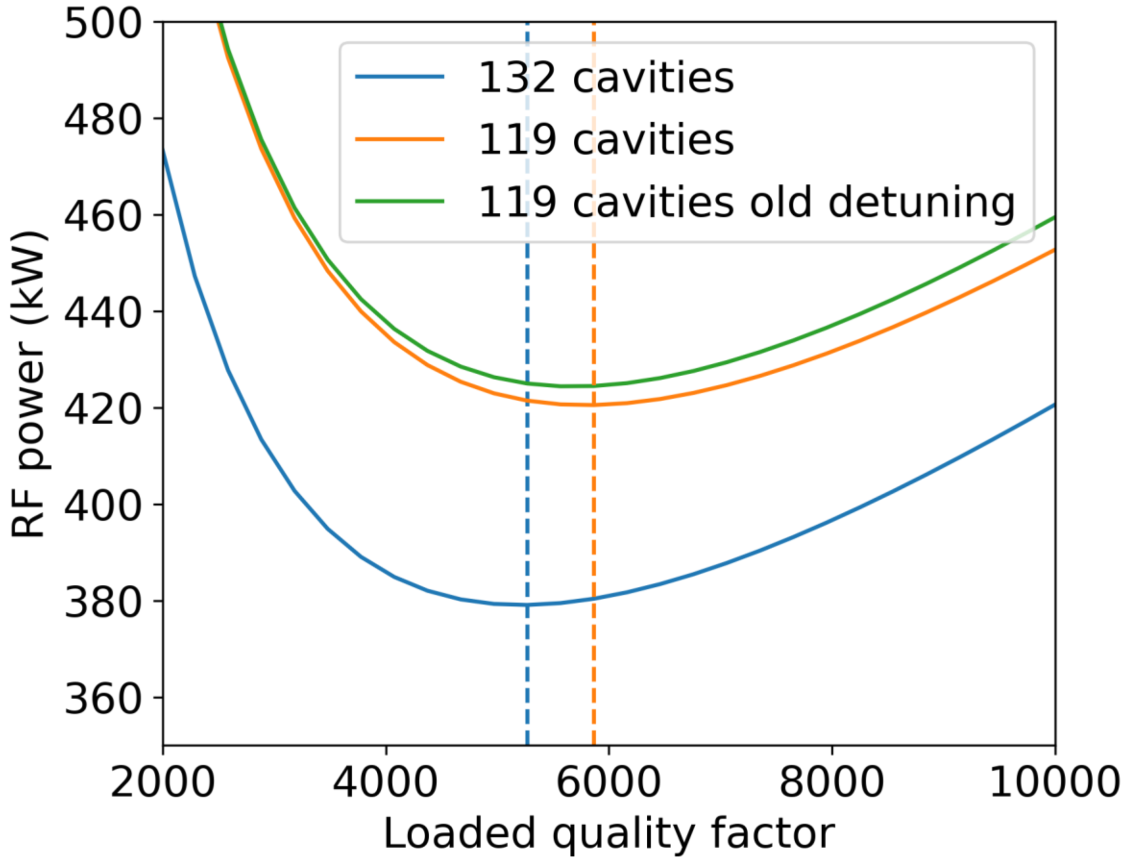
RF power overhead

To keep the same total voltage:
- RF voltage per cavity should be increased
- Detuning and Q_L can be kept constant (<10 kW of extra power)

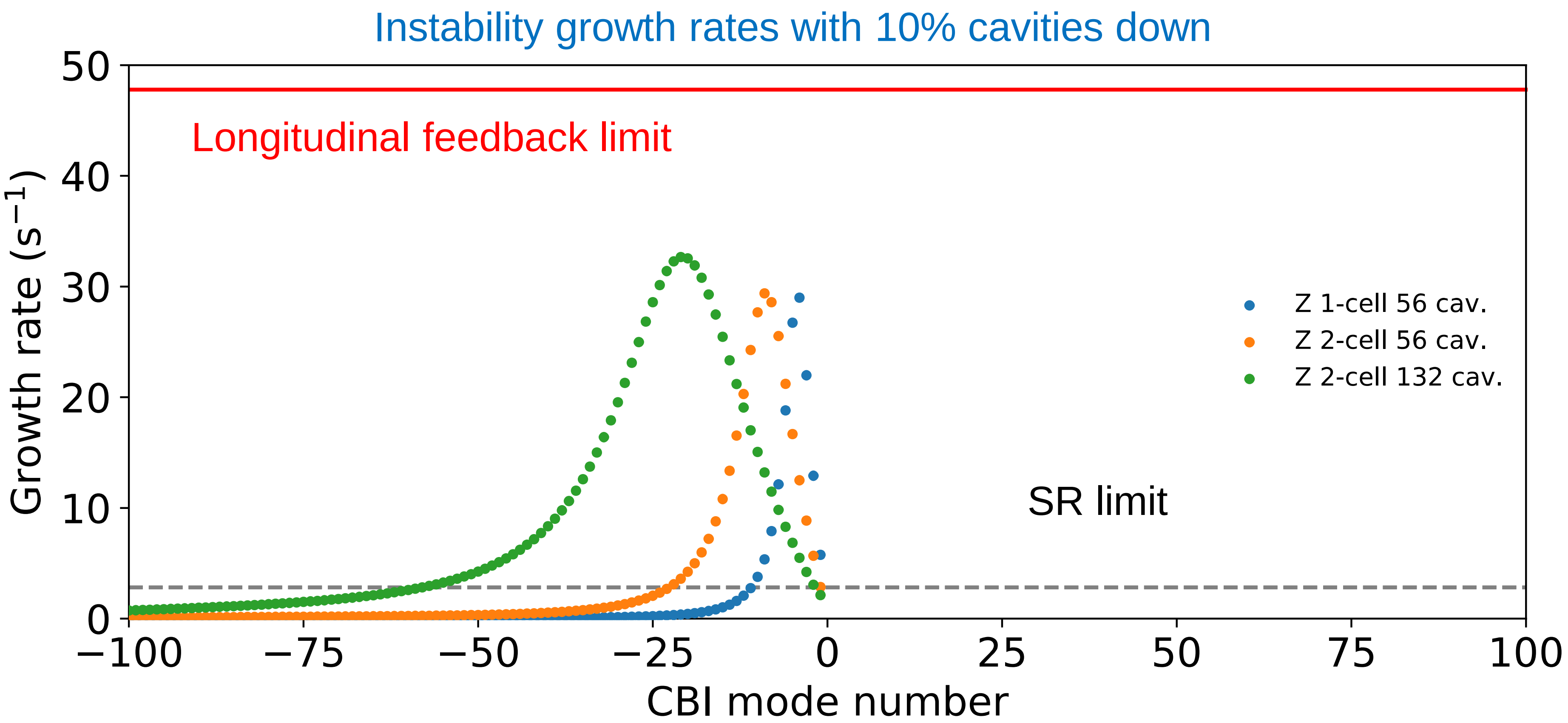
RF power per cavity should be increased from 0.38 to 0.43 MW to compensate for 10% fewer cavities

Similar conclusions for 132 2-cell cavities

Input RF power for optimum detuning for two scenarios (2-cell 132 cavities)



Impact of fundamental impedance



Coupled-bunch instability due to fundamental mode could be suppressed by a longitudinal feedback system (main RF system as kicker) with damping time of $2T_s$ *(see, D. Teytelman, FCC week, 2019),* but RF power requirements need to be evaluated

→ We are at the limit to reach 10% redundancy

Summary

The 2-cell design seems feasible for the nominal current at Z, but several critical aspects must be addressed:

- Need for adjustable/variable fundamental power coupler with wide range of coupling (>2 orders of magnitude)
- Presence of 0-mode requires additional longitudinal feedback system for stability (can potentially be avoided via design modification)
- Transverse feedback performance and integration should be carefully studied (also needed for 1-cell design, but less demanding)
- A 40%-increase of HOM power per cryomodule is not a showstopper if the 2-coax concept is demonstrated

Keeping the circulating beam with 10% fewer cavities is at the limit of stability given by longitudinal feedback system and requires ~10% RF power margin

Scenario	56 1-cell cav.	56 2-cell cav.	132 2-cell cav.
Beam loading compensation	Fixed FPC coupling with moderate Q_L	Wide-range of FPC coupling	Wide-range of FPC coupling + extremely low Q_L
CBI due to fundamental mode	Strong RF feedback	Strong RF feedback	Strong RF feedback Small margin (factor of 4)
Longitudinal CBI	No trapped HOMs	0-mode strong damping and/or longitudinal feedback	0-mode strong damping and/or longitudinal feedback
Transverse CBI	Weak TFB system is useful	TFB system with 100-turn damping time	TFB system with 50-turn damping time
Higher-order-mode power	"2-coax concept" needs demonstration	"2-coax concept" needs demonstration + 40% HOM power increase	"2-coax concept" needs demonstration + 40% HOM power increase
Availability challenges	Longitudinal feedback system (main RF system as kicker) + ~10% RF power margin		

Thank you for your attention!

Backup slides

Steady-state beam loading

RF power for SRF cavities with circulators *(e.g., J. Tückmantel, 2011)*

$$P = \frac{1}{2}\frac{V_{\mathrm{cav}}^2 Q_L}{(R/Q)}\left[\left(\frac{\omega_0 - \omega_{\mathrm{RF}} - \Delta\omega_{opt}}{\omega_{\mathrm{RF}}}\right)^2 + \frac{1}{4}\left(\frac{1}{Q_L} + \frac{1}{Q_{L,opt}}\right)^2\right]$$

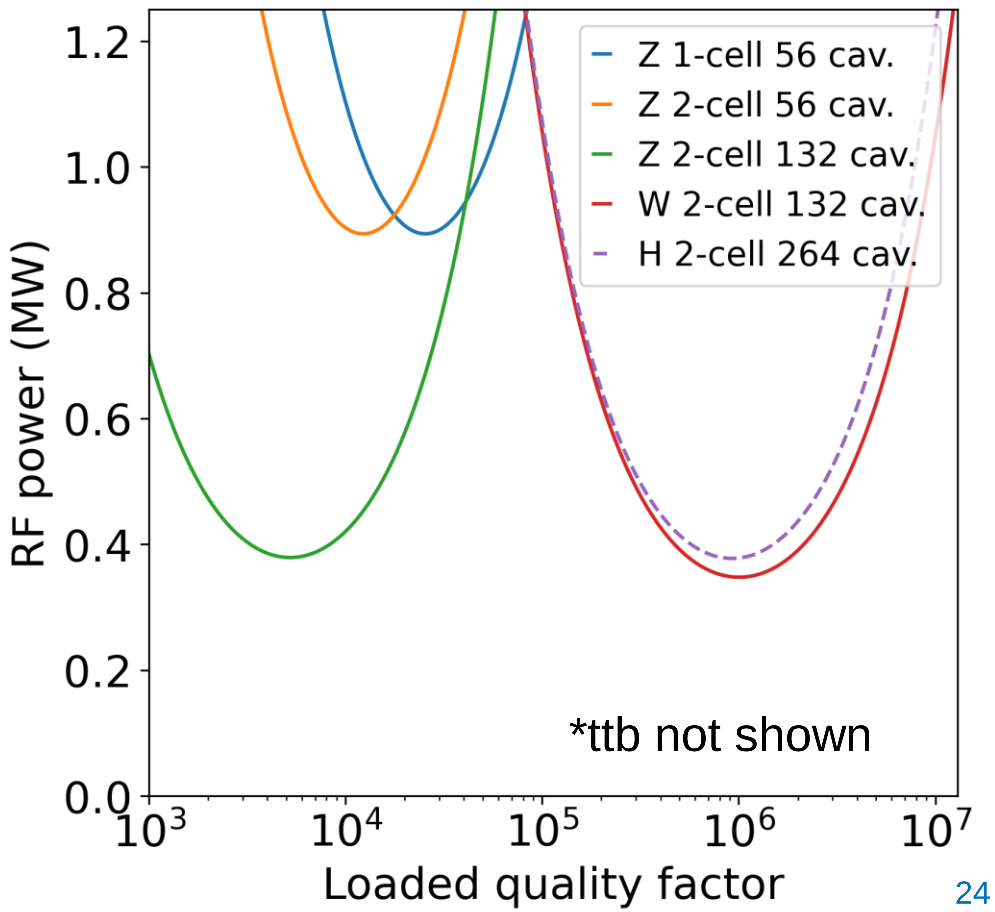
Optimal detuning $\Delta\omega_{opt} = -\dfrac{\omega_{\mathrm{RF}}(R/Q)\, I_{b,DC} \sin\phi_s}{V_{\mathrm{cav}}}$

Optimal quality factor $Q_{L,opt} = \dfrac{V_{\mathrm{cav}}}{2(R/Q) I_{b,DC} \cos\phi_s}$

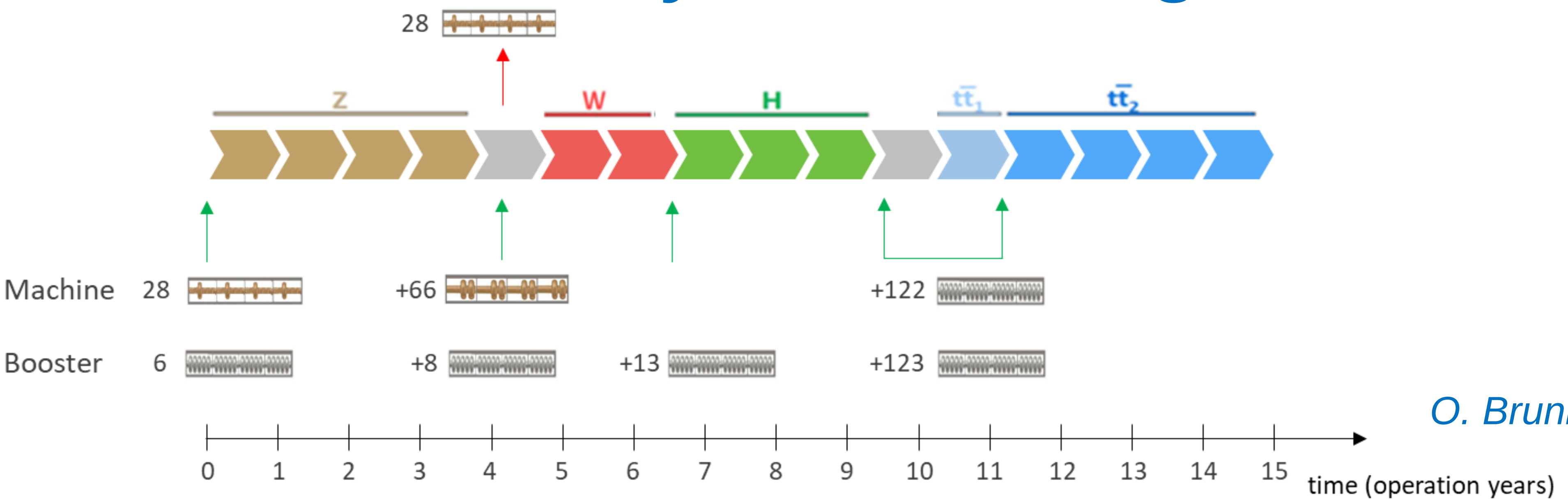
Increasing (R/Q) (43.8→90.6 Ohm) and reducing V_{cav} lead:
→ Large range for $Q_{L,opt}$ adjustment (a factor of ~75-600) starting from $\sim 5\times10^3$: possible FPC solutions under study *(S. Gorgi Zadeh and E. Montesinos, CERN SRF, 2024; see also slides of F. Gerigk)*
→ Doubled detuning enhances instability due to fundamental mode

Can the total voltage be increased for Z mode?

Input RF power for optimum detuning*



Baseline RF system configuration



O. Brunner

Motivation to avoid 1-cell design:

- Rationalization of RF resources during the development process (3 → 2 cavity types)
- Simplification of the installation sequence (no cryo-module removal)
- Potential savings (cost, manpower, and time)

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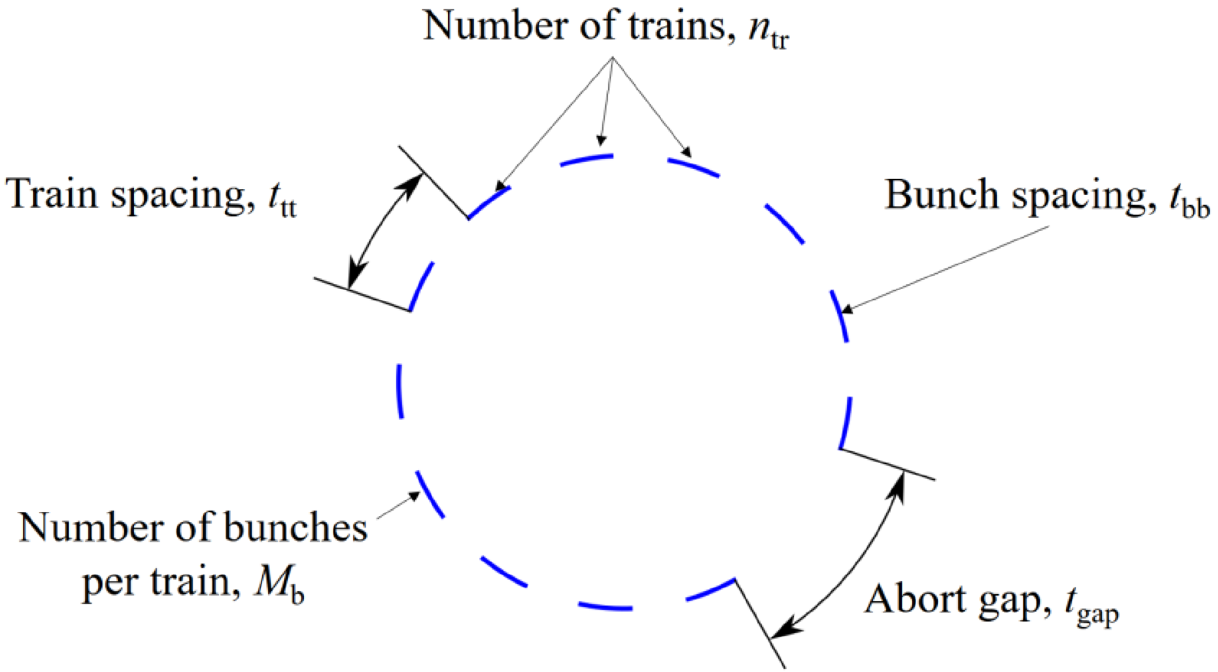
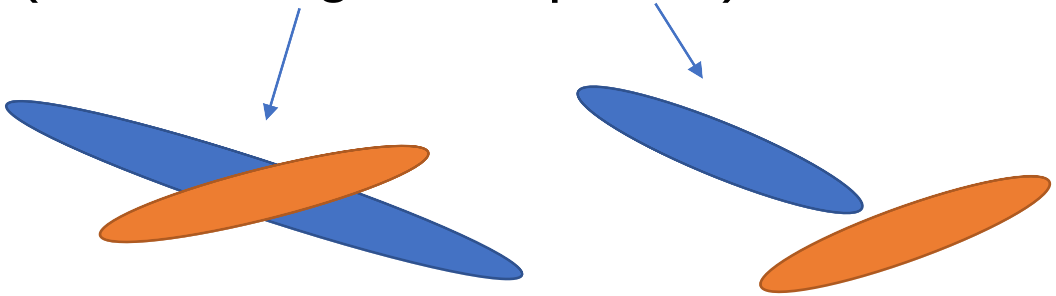
Transient beam loading



Gaps in machine filling will result in modulation beam parameters (bunch length and phase)



→ Might have impact on luminosity

Conventional approaches:

- Small-signal model in frequency domain*, which assumes small modulations (but we have 100% modulation of beam current!)
- Particle tracking simulations (difficult for 10000 bunches in FCC-ee Z)

→ We use steady-state time domain method**

** F. Pedersen, RF Cavity feedback, CERN/PS 92-59 (1992)*

*** J. Tückmantel, CERN Report No. CERN-ATS-Note-2011- 002 TECH, 2011*

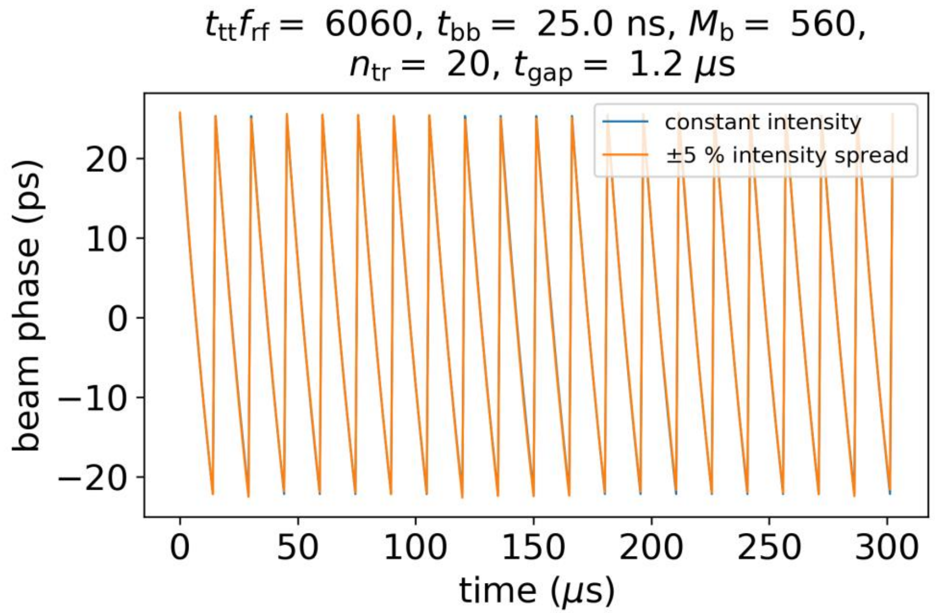
Beam phase modulation

Symmetric filling scheme reduces modulation of the beam phase

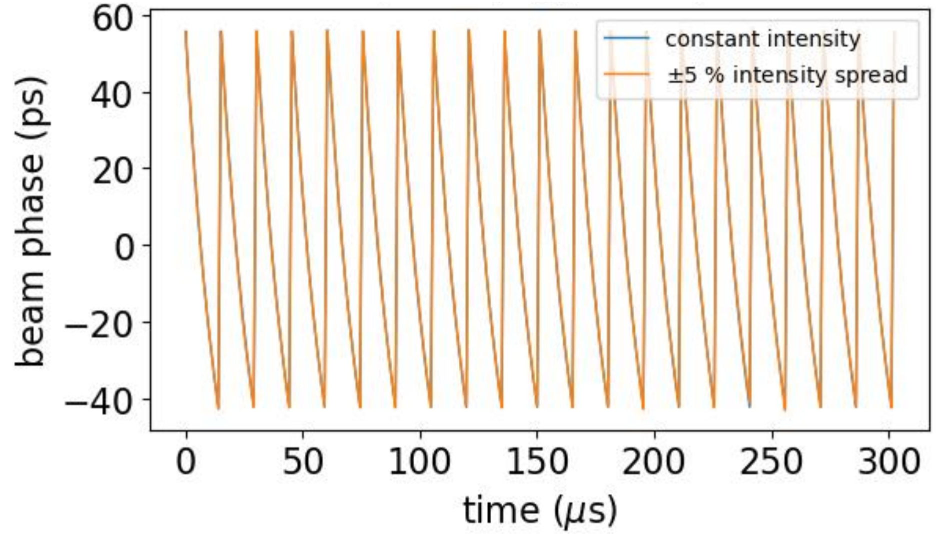
For identical rings, transients can be compensated by matching abort gaps (e.g., in PEPII, LHC,…)

Imbalance of charge results in different detuning for electron and positron beams
→ Slightly different transients
→ The collision point shift is negligible for $\pm 5\ \%$ random spread for both 1-cell and 2-cell designs

1-cell design



2-cell design



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